

Geophysical Investigation of the Sulphur Bank Mercury Mine Superfund Site, Lake County, California

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Abstract. Airborne geophysical reconnaissance was used to identify potential flow paths for mercury-rich, acidic water entering Clear Lake near the Sulphur Bank Mercury Mine. Airborne magnetic and electromagnetic conductivity surveys were conducted over a 12.3 km² (4.75 mi²) area that included the Oaks Arm of Clear Lake and the old mine. These surveys identified four magnetic and/or conductive anomalies that may represent groundwater conduits towards or away from the Herman Impoundment. An anomaly that extended from Herman Impoundment through a waste rock dam and into Clear Lake was selected for a more detailed ground electromagnetic conductivity survey. The combined results of the airborne and ground surveys provided a detailed, lateral depiction of conductive zones, the most probable pathways for groundwater flow. These surveys also identified near-surface areas that may contain elevated concentrations of sulfide minerals that weather to produce acid groundwater.

Key words: electromagnetic surveys; magnetic surveys; Sulphur Bank Mercury Mine; Superfund

Introduction

Geophysical surveys can quickly provide insight into the geology and hydrology of a project area. The intent of this study was to use airborne geophysical reconnaissance techniques to identify magnetic and conductive anomalies that may represent permeable corridors for the flow of contaminated groundwater. Surface geophysical surveys were performed to better delineate the conductivity anomalies observed in the airborne data. Geophysical techniques can have multiple interpretations that adequately explain observations; therefore, interpretations were verified by comparison with down-hole geophysical logs, a detailed hydrologic model, and a site geologic map independently developed by Tetra Tech EM, Inc.

Ideally, airborne geophysical surveys should be used early in a site investigation to quickly delimit areas of interest for more detailed ground investigations. This approach reduces costs by focusing expensive drilling activities on smaller areas. The Sulfur Bank Mercury Mine (SBMM) was an excellent site to evaluate

geophysical techniques because an extensive network of groundwater monitoring wells had already been established there as part of a remedial investigation/feasibility study.

Fugro Airborne Services flew the airborne geophysical reconnaissance of the Oaks Arm of Clear Lake (including the SBMM) on August 9-17, 2000. The spacing between each flight line was 50 m and the nominal station spacing was approximately every 3 m along the line. The data from these flights were independently interpreted by D. McConnell (Fugro Airborne Services 2000) and R. Hammack (Hammack et al. 2002a, b). A ground geophysical survey was then conducted to corroborate findings of the airborne survey. The results of both surveys were confirmed with geologic and hydrologic information for the SBMM Superfund Site wells (EPA 1994).

Site Description

The SBMM comprises approximately 49 ha (120 acres) of disturbed ground, including piles of low-grade ore, waste rock, or tailings and a flooded open-pit mine now known as the Herman Impoundment (Figures 1 and 2). Herman Impoundment covers approximately 9.3 ha (23 acres) and is about 33 m (100 ft) deep. A smaller pit (Northwest Pit) is located about 175 m (575 ft) northwest of Herman Impoundment. Most of the waste rock excavated from the open pits was disposed of in an elevated area between Herman Impoundment and Clear Lake (Waste Rock Dam). The SBMM was initially mined for sulfur during 1865-68. From 1899 until 1918, mercury ore was intermittently mined at the site using underground methods. Most of the mercury ore was mined from open pits between 1922 and the mine's final closure in 1957 (White and Roberson 1982).

The SBMM is located in the southern part of the Northern Coast Ranges of California. The predominant bedrock is graywacke and argillite of the Jurassic to Eocene Franciscan Complex and is overlain by Quaternary andesitic lava from vents northeast of the study area. Other lava sources could be vents directly northwest of Herman Impoundment on Rattlesnake Island (Hearn et al. 1995). The lava

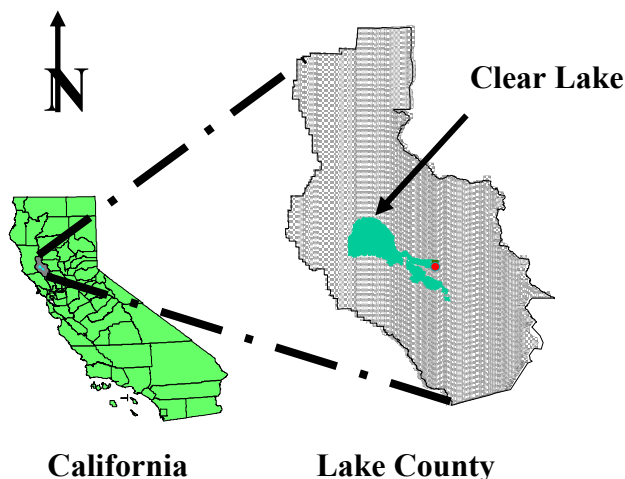


Figure 1. Map showing the California location of the Sulphur Bank Mercury Mine Superfund Site

flows are part of the Clear Lake Volcanics, a sequence of volcanic flows and domes that range in composition from rhyolite to basalt. The Franciscan Complex in the southern part of the study area consists of a thick sequence of metamorphosed sandstone, conglomerate, argillite, basalt, amphibolite, and serpentinite. Unconsolidated Quaternary lake sediments overlie Franciscan bedrock in areas adjacent to Clear Lake but underlie the andesite flow (White and Roberson 1962).

Thermal modeling indicates that a shallow (4 to 5-km depth) body of cooling magma underlies the SBMM and is responsible for the strong geothermal activity in the immediate area (Stimac et al. 2001). The Sulphur Bank Mine Stock is one part of a complex of magma bodies underlying the Clear Lake volcanic field west and south of SBMM (Isherwood 1975; Stimac et al. 2001).

Results and Discussion

Magnetic Surveys

Figure 3 is an airborne, total magnetic field map of eastern Clear Lake that shows the extent of an andesite flow that underlies the SBMM and much of the Oaks Arm of Clear Lake. The lava flow contrasts sharply with surrounding lake sediments because of the high magnetic susceptibility and the high remnant magnetism of minerals (e.g., magnetite and pyrrhotite) in the lava. Potential fault zones within the lava flow appear as magnetic “lows” because magnetic minerals are often altered during faulting and magnetism is destroyed. Potential faults interpreted from magnetic data are shown in Figure 4. The magnetic signature of fault zones is less apparent in the vicinity of Herman Impoundment. One reason is that the pervasive alteration of the andesite flow in

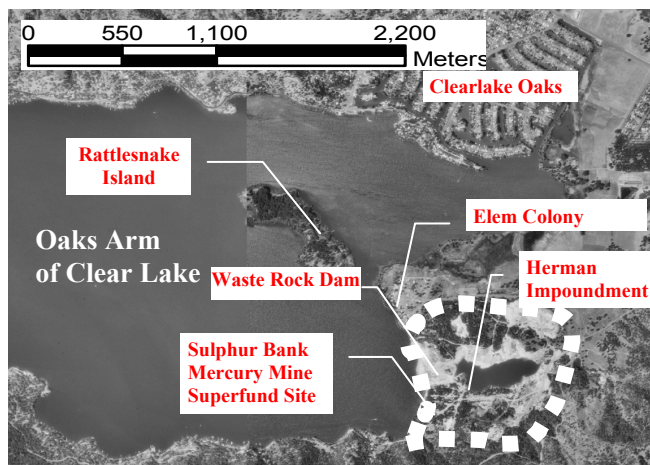


Figure 2. Aerial photograph of Sulphur Bank Mercury Mine and surroundings

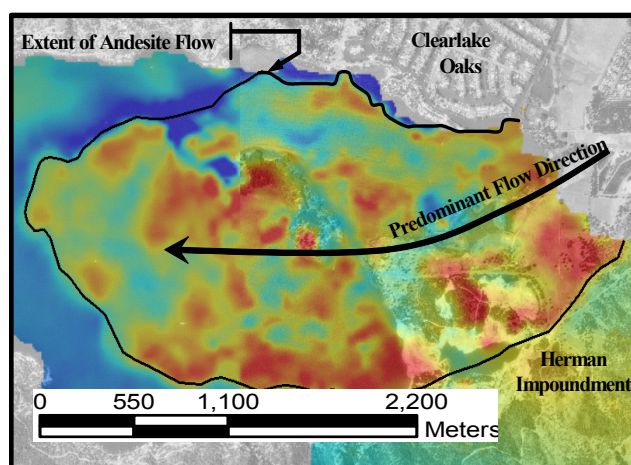


Figure 3. Airborne total field magnetic map of Oaks Arm of Clear Lake

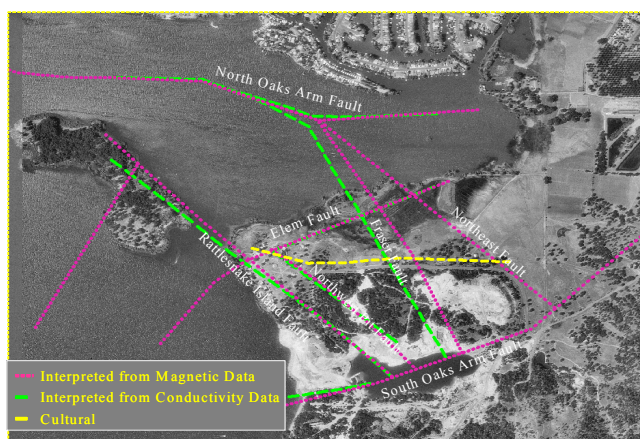


Figure 4. Fault map of Sulphur Bank Mercury Mine the vicinity of Herman Impoundment would likely have destroyed magnetic minerals. Another reason is

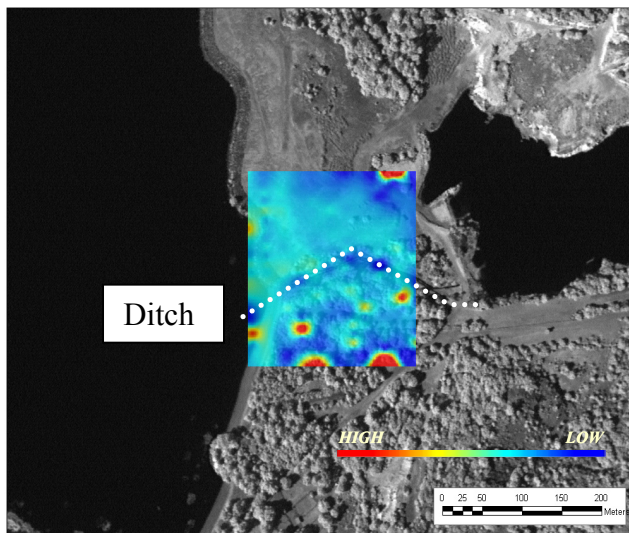


Figure 5. Total field magnetic map from the ground survey

that during mining, the andesite was excavated from the area of Herman Impoundment and processed for mercury recovery or relocated to waste rock dumps.

A ground-based, total field magnetic survey was conducted on part of the waste rock dam (Figure 5). Although originally intended to be a vertical-gradient magnetic survey with two cesium sensors, one sensor malfunctioned, and the survey had to be completed as a total field magnetic survey. Total field magnetic surveys require a base station to correct data for diurnal variations in the earth's magnetic field. Such a base station was not available on site. To minimize errors, the total field magnetic survey was conducted in the early morning when diurnal variations are minimal. Moreover, data from a USGS Geomagnetic Observatory in Fresno, Ca showed only slight variations (± 5 nT) in the earth's magnetic field during the time of the survey. The lack of a base station only minimally compromised the results of the ground magnetic survey.

Figure 5 is a map of the results of the ground total field magnetic survey. Conspicuous anomalies in red indicate the locations of ferrous metal scrap discarded at the site. The drainage ditch that extends from Herman Pit to Clear Lake displays a low magnetic field (blue), which indicates that the material beneath the ditch is probably of a different geologic origin than the mine waste rock piles to the north and south.

Airborne EM Conductivity Surveys

Figure 6 is a map showing the location of small, discrete airborne conductivity anomalies that are referred to in the discussion below. Figures 7, 8, 9, 10, 11, and 12 are airborne conductivity maps of the

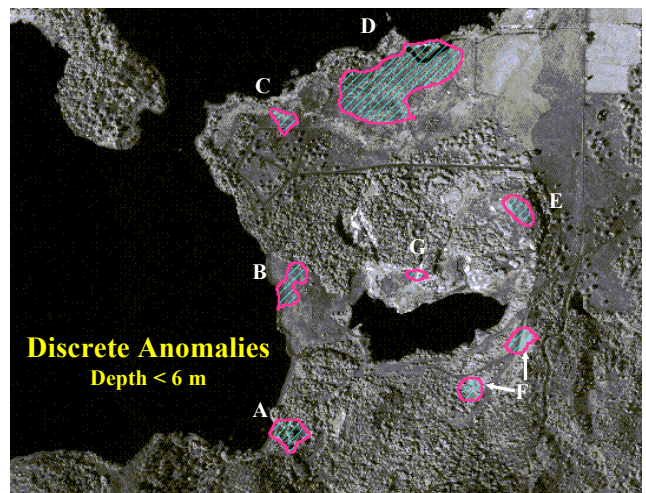


Figure 6. Location of shallow anomalies identified in the airborne data

eastern Clear Lake region collected using transmitter frequencies of 56 kHz, 25 kHz, 7200 Hz, 6200 Hz, 1500 Hz, and 900 Hz, respectively. The use of 6 different frequencies permitted exploration to 6 different depths; exploration depth increases with decreasing frequency and decreasing ground conductivity (see Appendix I).

56 kHz

Figure 7 is an apparent conductivity map collected at a frequency of 56 kHz. Data at this frequency indicates conductivity from the earth's surface to depths ranging from 2.5 m (8 ft) in the most conductive areas (darkest red) to 33 m (110 ft) in the most resistive areas (darkest blue). Most of the anomalous area identified from 56 kHz data is within 3 m (10 ft) of the surface. The anomalies consist of the SBMM anomaly, which is directly connected to the Herman Impoundment and other anomalies originating from discrete sources (anomalies A-G, Figures 6 and 7). The SBMM anomaly includes the Herman Impoundment, a conductive corridor that extends from Herman Impoundment through the waste rock dam to Clear Lake, and a conductive plume beneath Clear Lake that extends north and south along the shoreline.

Note that the SBMM anomaly (G) extends beyond the limits of Herman Impoundment to the north and west but is largely contained within the impoundment to the south and east. This probably reflects the permeability of the faulted and altered andesite that forms the north pit wall and the broken waste rock dam that forms the west wall. Conductive water from the impoundment saturates these permeable zones and is the source of the anomaly. The conductive corridor through the waste rock dam is the most likely

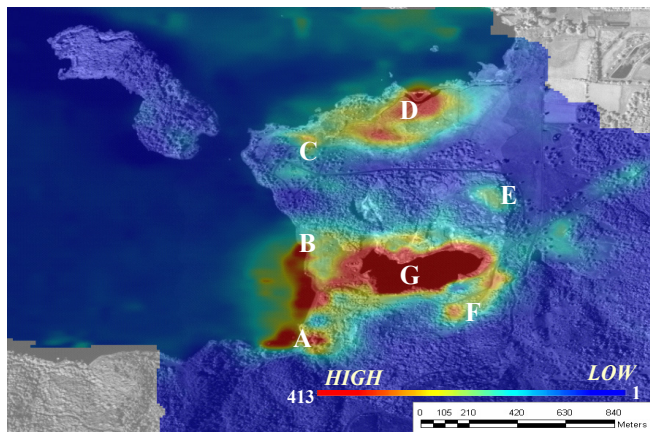


Figure 7. Airborne conductivity data (mS/m) acquired at a frequency of 56 kHz

flow path for Herman Impoundment water flowing into Clear Lake.

Anomaly A is located south of a major northeast-trending fault (South Oaks Arm Fault, Figure 4) and is separated from the SBMM anomaly by an area of lesser conductivity. Normally resistive rocks of the Franciscan Complex underlie this anomalous area. Air photos show that the on-shore portion of this anomaly is an area that contains a house and outbuildings typical of a small farmstead. Fences and metal roofing are common sources of conductive anomalies so a cultural origin was initially suspected. However, the anomaly extends westward (Figure 7) beneath Clear Lake where it is unlikely that the anomaly is of cultural origin. This anomaly could indicate the presence of conductive groundwater and originate from a discrete source (e.g., acidic water generated by the localized weathering of sulfidic mine waste).

Anomaly B is located on the waste rock dam near the Clear Lake shoreline (Figures 6 and 7). Although Anomaly B merges with the SBMM anomaly within Clear Lake, it may represent a separate source of acid groundwater within the waste rock dam. Conversely, anomaly B could represent a secondary pathway for water flowing from Herman Impoundment to Clear Lake. The possible secondary flow path is better shown in the 25 kHz (Figure 8) results below.

Anomaly D is in a wetland area that is separated from Clear Lake by a dike built of scoria and waste rock from SBMM. During mining, this area was used as a settling pond for water pumped from Herman Pit (now Herman Impoundment). The near-surface conductivity at this locality could result from conductive clays that underlie the wetland and/or from acidic water formed by the oxidation of sulfidic fines deposited in this area by mine dewatering

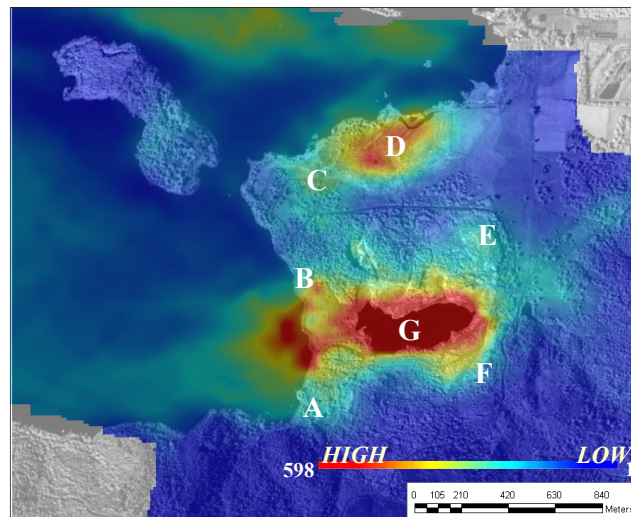


Figure 8. Airborne conductivity data (mS/m) acquired at a frequency of 25 kHz

activities. Anomaly C appears to be a continuation of the wetland anomaly. Anomaly E is located in a waste rock dump and probably represents acidic groundwater from weathering sulfide minerals. Anomaly F is located southeast of the impoundment. This anomaly coincides with piles of mine waste and probably represents acidic groundwater.

25 kHz

The SBMM anomaly (G) for 25 kHz data is similar to the 56 kHz anomaly previously described. The SBMM anomaly at Herman Impoundment extends further into the bedrock that surrounds the pit. Moreover, the conductive corridor that extends through the waste rock dam between Herman Impoundment and Clear Lake is broader in the 25 kHz data than in the 56 kHz data. This indicates that aquifers occur within the conductive corridor at depths between 2.5 m (from 56 kHz data) and 3.7 m (from 25 kHz data). Anomalies A, C, E, and F (Figures 6, 7, and 8) identified in the 56 kHz data are weak or absent in the 25 kHz data. This indicates that these anomalies have a very shallow origin that is less than 4 m in depth. Anomaly B, in 25 kHz data (Figure 8), extends further into the waste rock dam than in the 56 kHz data and exhibits two nodes of higher conductivity. The northernmost node coincides with the location of a cluster of monitoring wells that could cause a false anomaly. Zones of lesser conductivity extend southeast from these nodes towards Herman Impoundment. Although anomaly B is thought to result from local weathering of sulfide minerals, the location and orientation of these nodes may suggest a secondary pathway for groundwater flow from Herman Impoundment to Clear Lake.

A conductive anomaly within the Oaks Arm of Clear Lake (Figure 8) is clearly evident in the 25 kHz data. This anomaly directly overlies the North Oaks Arm Fault (Figure 4), a major fault that was interpreted from magnetic data. The fault may provide a pathway for conductive hydrothermal waters to flow upward through the normally resistive volcanic rocks that underlie this area. Alternative explanations include: 1) conductive clay minerals in alteration zones along the fault, 2) conductive sediment accumulations in topographic low areas overlying the fault, or 3) metal sulfide deposits along the fault trace.

7200 Hz

Figure 9 is an apparent conductivity map collected at a frequency of 7200 Hz. This data represents conductivity from the surface to depths ranging from 7 m (23 ft) in the most conductive areas (darkest red) to 94 m (308 ft) in the most resistive areas (darkest blue). The anomalous areas identified from 7200 Hz data are within 8.5 m (28 ft) of the surface. The 7200 Hz SBMM anomaly (G) is similar to that of the previously discussed data except that the width of the conductive corridor through the waste rock dam is narrower and the areal extent of the plume beneath Clear Lake is less at the exploration depth of 7 m.

Anomaly B is present in the 7200 Hz data and remains connected to the main SBMM anomaly, which supports the hypothesis that the anomaly can be interpreted as a groundwater flow path from the Herman Impoundment into Clear Lake.

The wetland anomaly (Anomaly D) becomes linear in nature and occurs at the intersection of the Fraser and Elem Faults (Figure 4). The anomaly extends northwest along the Fraser Fault. A second anomaly is located at the intersection of the Fraser and North Oaks Arm Faults. Conductive materials may be associated with these faults. Anomaly C, an extension of anomaly D in the higher frequencies, becomes a clear and distinct anomaly at this frequency (Figures 6 and 9). The anomaly is at the intersection of the Northwest Pit and Elem Faults (Figure 4), and may be connected to Herman Impoundment via the faults. Anomaly E, in the Northeast Waste Rock Dump, is present in the 56 kHz data, weak or absent in the previous data sets, and strong in the 7200 Hz data. Anomaly F exhibits the same pattern. This could be an indication of a near surface and a deeper conductive zone within these waste piles.

6200 Hz

Figure 10 is an apparent conductivity map collected at a frequency of 6200 Hz. Conductivity data at this

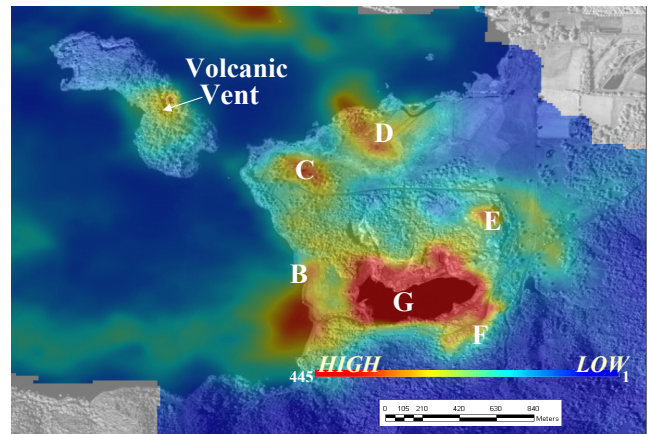


Figure 9. Airborne conductivity data (mS/m) acquired at a frequency of 7200 Hz

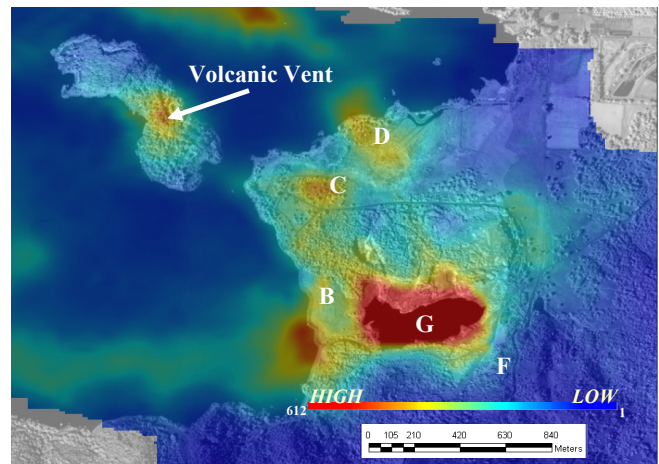


Figure 10. Airborne conductivity data (mS/m) acquired at a frequency of 6200 Hz

frequency pertains to earth from the surface to depths ranging from 7.5 m (25 ft) in the most conductive areas (darkest red) to 100 m (330 ft) in the most resistive areas (darkest blue). The anomalies identified from the 6200 Hz data are within 9 m (30 ft) of the surface.

The SBMM anomaly (G) for 6200 Hz data includes the Herman Impoundment and a separate anomaly beneath Clear Lake. Evidence for the conductive corridor between the impoundment and the lake still exists, but it is not as strongly defined. Compared with 7200 Hz data, the 6200 Hz anomaly at the impoundment extends further into the bedrock that comprises the northern pit wall. This is especially noticeable in fault zones (Figure 4). The portion of the SBMM anomaly beneath Clear Lake is greatly reduced from that of the 7200 Hz data.

Anomaly B is no longer directly connected with the Herman Impoundment part of the SBMM anomaly. Rather, it is represented by two small anomalies within the waste rock dam. Anomaly C occurs at the

intersection of the Northwest Pit Fault and the Elem Fault (Figure 4). The shape of Anomaly D in the 6200 Hz data is clearly more influenced by the Fraser Fault than the Elem Fault (Figure 4). Anomaly F is smaller in the 6200 Hz data than in the 7200 Hz data, and is shifted slightly towards the southeast.

1500 Hz

Figure 11 is an apparent conductivity map collected at a frequency of 1500 Hz. This data represents conductivity from the surface to depths ranging from 15 m (100 ft) in the most conductive areas (darkest red) to 200 m (650 ft) in the most resistive areas (darkest blue). The anomalous areas identified from 1500 Hz data are within 18 m (60 ft) of the surface. In the 1500 Hz data, the SBMM anomaly exhibits a pronounced extension towards the northwest along the Rattlesnake Island Fault (Figures 4 and 11). The anomaly only occupies the northern part of the open pit, possibly reflecting the bathymetry of the impoundment at 18-m (60-ft) depth or the trace of the South Oaks Arm Fault. The lobe of the SBMM anomaly that extends westward through the waste rock dam and into Clear Lake is restricted to the trace of the South Oaks Arm Fault.

Anomaly C is smaller in the 1500 Hz data than in the 6200 Hz data, and is shifted slightly toward the southeast, indicating that the geologic or hydrologic feature responsible for the anomaly may be dipping toward the southeast. A conductive anomaly that is present in lower frequency data (yellow line, Figure 4) and closely parallels the road to the Elem Colony has the characteristic signature of a pipeline and is presumed to be of cultural origin.

900 Hz

Figure 12 is an apparent conductivity map collected at a frequency of 900 Hz. Conductivity data obtained at this frequency pertains to earth from the surface to depths ranging from 40 m (130 ft) in the most conductive areas (darkest red) to 265 m (870 ft) in the most resistive areas (darkest blue). The anomalous areas identified from 900 Hz data are within 24 m (79 ft) of the surface. With increasing exploration depth, SBMM anomaly is evident along the Northwest Pit Fault in the 900 Hz data. The deep anomaly in the general area of surface Anomaly D has extended both northward and southward along the Fraser Fault and the lobe of the SBMM anomaly (G) through the waste rock dam and beneath Clear Lake continues to decrease in area, whereas the northwest lobe of the SBMM anomaly extends further northwestward along the Rattlesnake Island Fault. A small lobe of the may merge with the SBMM anomaly. This anomaly has

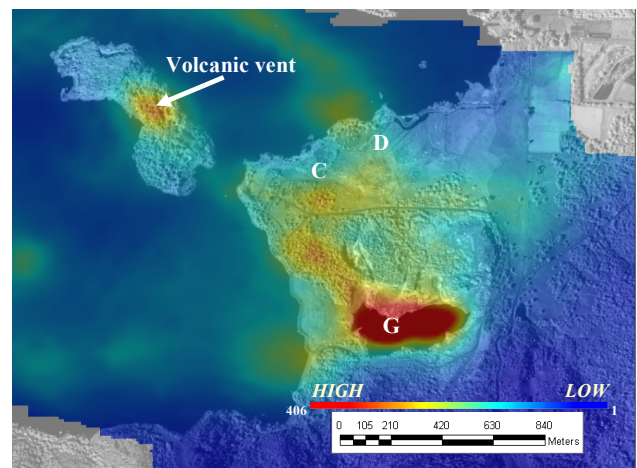


Figure 11. Airborne conductivity data (mS/m) acquired at a frequency of 1500 Hz

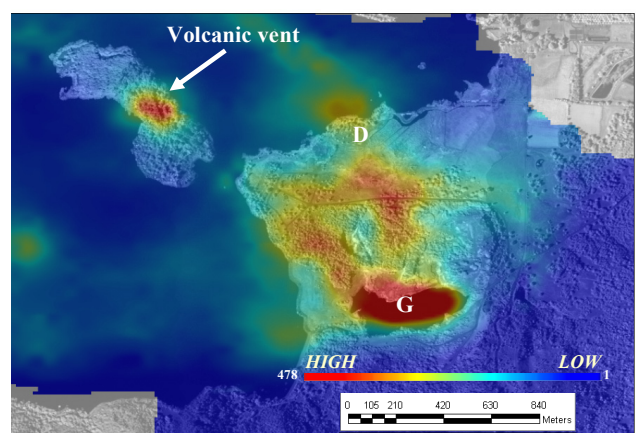


Figure 12. Airborne conductivity data (mS/m) acquired at a frequency of 900 Hz

also expanded in an east-west direction, but the expansion may be of cultural origin.

Ground Conductivity Surveys

The results of ground conductivity surveys of the waste rock dam are shown in Figures 13a, b, and c. The anomalies observed in the airborne data were used to target areas for ground geophysical surveys. Figure 13a depicts the results of a survey conducted using a Geonics EM34-3XL electromagnetic conductivity instrument in horizontal dipole configuration with an intercoil separation of 20 m. The results of this survey pertain to the apparent conductivity of the earth from the surface to a depth of about 15 m (50 ft) although the response of the instrument is heavily weighted to depths less than 2 m (6.5 ft). The results of this survey show a conductive anomaly in low-lying areas adjacent to Herman Impoundment. The anomaly probably indicates the extent to which conductive water from the impoundment is infiltrating into the near-surface layers of the waste rock dam. This conductive

anomaly is bound on the west by an area of lower conductivity that runs approximately north-south through the eastern one half of the survey area. The existence of this low-conductivity band indicates an impermeable area where water is not infiltrating through the near-surface materials that comprise the waste rock dam. Note that the low-conductivity area even extends across the ditch that runs between Herman Impoundment and Clear Lake. Conductive anomalies west of the low-conductivity band may represent near-surface areas of acid groundwater formed *in situ* by the weathering of sulfide minerals. Alternatively, these conductive anomalies may reflect the presence of imported ground-cover materials.

Figure 13b contains the results of an EM34-3XL survey conducted in vertical dipole configuration with a 20-m intercoil separation. Results of this survey pertain to the apparent conductivity of the earth for depths between 3 m (10 ft) and 18 m (60 ft). The results of this intermediate-depth survey show a conductive band extending east-west across the waste rock dam that roughly follows the contours of an existing ditch. This may indicate the location of an intermediate-depth, groundwater pathway between Herman Impoundment and Clear Lake.

Figure 13c contains the results obtained by plotting the difference between the EM34-3XL data vertical dipole data obtained at an intercoil spacing of 40 m and vertical dipole data acquired at an intercoil spacing of 20 m. It shows the apparent conductivity from 18 m (60 ft) to a maximum exploration depth of 60 m (197 ft). This map shows the location of several narrow, finger-like anomalies that extend across the waste rock dam in an east-west direction. These anomalies probably indicate the location of deep groundwater flow paths within the waste rock dam.

Conclusions

Geological Information

Geophysical data from airborne and ground surveys provided new information about the SBMM that may aid remediation efforts at the site. The fault locations and geologic contacts obtained from the geophysical surveys agree well with regional geologic maps (Hearn et al. 1995). The geophysical surveys also revealed many additional features.

Airborne magnetic data identified the extent of lava flows both on land and beneath Clear Lake. These lava flows had not previously been mapped beneath Clear Lake. Airborne geophysical surveys were also used to delineate faults based on magnetic and conductivity indications. In most cases, the fault

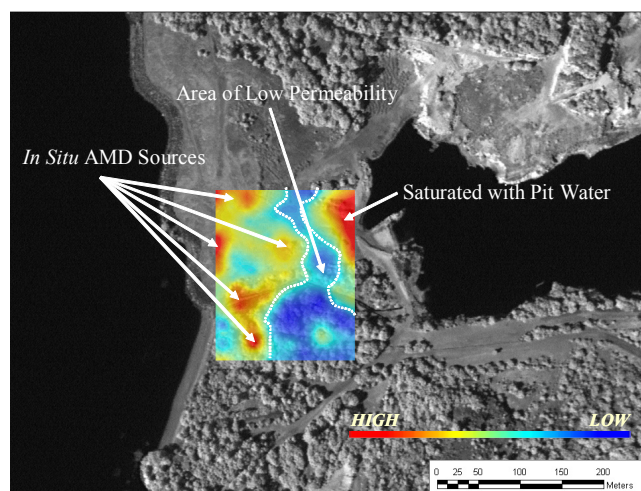


Figure 13a. EM34-3XL data (horizontal dipole; 20 m coil separation)

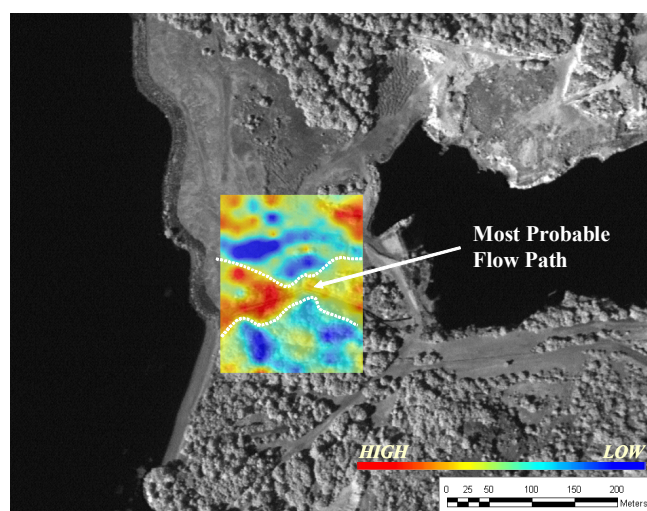


Figure 13b. EM34-3XL data (vertical dipole; 20-m coil spacing)

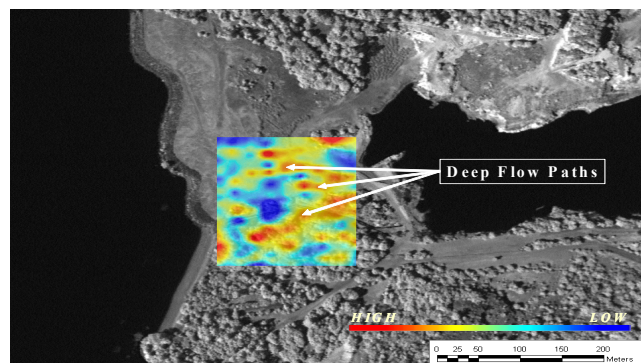


Figure 13c. Response curves that relate EM34-3XL data (vertical dipole, 20-meter and 40-meter coil separation) to conductivity measurements from a borehole log

indications from magnetic data were corroborated by fault indications from conductivity data. One exception is the Fraser Fault (Figure 4), where the fault location based on conductivity is about 90 m west of the fault indication based on magnetic data.

This study showed that three faults intersect the South Oaks Arm Fault within the Herman Impoundment (Figure 4). Although others had noted these faults in mine exposures, this study was the first to map these structures away from the open pit and beneath Clear Lake. The location of these faults is important because each is a potential groundwater flow path. However, the results of this survey must be combined with a hydrological investigation to determine groundwater flow rate and direction.

The location of the South Oaks Arm Fault was based on conductivity anomalies within the waste rock dam and beneath Clear Lake, as well as the assumption that the fault's up-thrown southern block confined the lava flow. Therefore, in the area of the SBMM, the fault is believed to be coincident with the southern margin of the lava flow, which is delineated in the magnetic data.

Rattlesnake Island Fault extends northwest from Herman Impoundment and across Rattlesnake Island. The location of this fault was established based on strong magnetic indications plus the location of discontinuous conductivity anomalies. There is a conductive anomaly on Rattlesnake Island, a volcanic vent that coincides with the fault. The conductivity anomalies along the trend of this fault become stronger with depth, which may indicate that an area of geothermal activity or conductive lake sediments exists below the lava flow. At the lowest frequency (900 Hz), the conductive anomalies north of Herman Impoundment merge to form a broad conductive area. The Rattlesnake Island Fault could be a groundwater conduit between Herman Impoundment and inhabited areas to the north. The Northwest Pit Fault parallels the Rattlesnake Island Fault. The location of this fault is based on both magnetic and conductivity indications. Magnetic results indicate that this fault may be a part of the Rattlesnake Island Fault Zone. This fault is the most likely conduit for the emplacement of mineralization at the Northwest Pit.

The Fraser Fault extends north-northwest from Herman Impoundment and intersects the North Oaks Arm Fault in Clear Lake, just south of Charter Oaks. The fault location determined from magnetic indications is about 90 m east of the location based on conductivity results. This may be due to a dipping fault plane. The fault conductivity data shows more defined trends; therefore, the location of the fault is

interpreted to coincide with the conductivity results. Magnetic material from the open pit has been relocated to this area and may confuse interpretations based on magnetic indications. The Fraser Fault appears to connect the South Oaks Arm Fault with the North Oaks Arm Fault and may be a major conduit for groundwater flow.

The Northeast Fault was located based on magnetic data. There are only weak conductivity indications that corroborate the existence or location of this fault. The Northeast Fault is not considered a potential pathway for groundwater flow.

The Elem Fault is a northeast-trending fault that is indicated by both magnetic and conductivity data. Conductivity data suggest that this fault may be an important conduit for deep groundwater flow.

Hydrologic Flowpath through the Waste Rock Dam

The best testimony to the utility of geophysical surveys is provided by Figure 14, where a dense network of groundwater monitoring wells, emplaced at considerable cost, missed the most probable pathway for groundwater flow through the waste rock dam. Both airborne and ground conductivity data delineated the most probable path that water is taking from Herman Impoundment through the waste rock

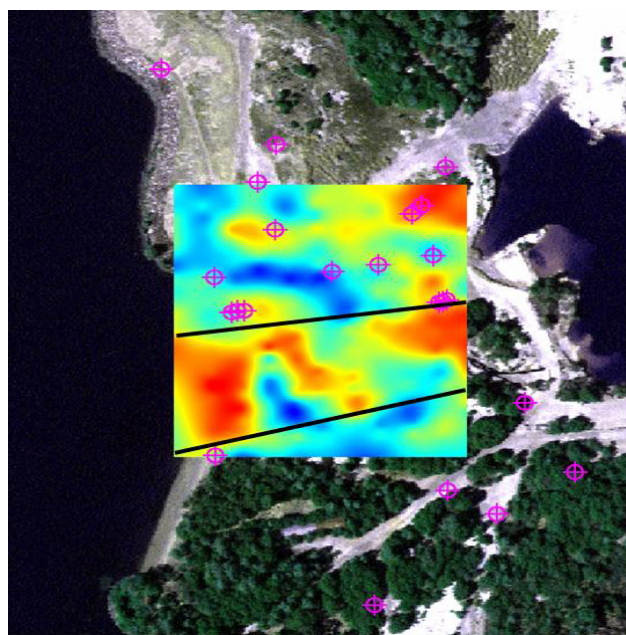


Figure 14. EM34-3XL apparent conductivity map of the waste rock dam showing the most probable pathway for groundwater flow between Hermann Impoundment and Clear Lake (between the two black lines); symbol (⊕) denotes the location of groundwater monitoring wells that were drilled as part of the remedial investigation at the site

dam to Clear Lake (Figures 7-12, 13b, and 13c). The location of the groundwater flowpath probably is influenced most by the highly permeable, coarse material at the base of the waste rock dam. However, the flowpath, as depicted in these figures is also coincident with the edge of the lava flow and the South Oaks Arm Fault, which may provide groundwater conduits through the waste rock dam. Had the geophysical survey been performed before the wells were drilled, well placement would have been better and more useful information would have been obtained. Better well location provided by geophysical surveys can save both time and money in remedial investigations.

Locations of Weathering Sulfidic Wastes

Figures 6 and 7 shows the location of discrete areas of anomalous, near-surface conductivity that are weak or absent in maps of lower frequencies. We believe that many of these conductive anomalies represent acidic, metal-containing plumes that are due to the weathering of waste rock, low-grade ore, or tailings in an aerobic, near-surface environment.

Recommendations

- Airborne and ground conductivity data show the most likely flowpath taken by groundwater flowing from Herman Impoundment through the waste rock dam to Clear Lake. Use these maps to locate additional drill holes and verify the existence of this potential flowpath.
- Site additional drill holes on faults that extend northward from Herman Impoundment to determine whether or not these faults are an avenue for groundwater flow.
- Investigate the near-surface anomalies identified in these surveys, as they may identify acid-generating material that should be relocated.
- Use the conductive anomalies beneath Clear Lake as a basis for detailed sampling of contaminated sediments.

Important caveats to remember when using this information include:

- Conductivity surveys can identify likely groundwater flow paths but do **not** indicate groundwater flow direction or flow rate.
- Conductive anomalies at SBMM are thought to be predominantly water-related because of the high conductivity of Herman Impoundment water and geothermal water. However, the probable existence of

other geologic conductors such as clay deposits and sulfide minerals must be considered.

- Conductive and magnetic anomalies of cultural origin are usually recognized and easily screened. This is especially true for the SBMM site where recent high-resolution, multispectral imagery helped us distinguish cultural anomalies. However, it is possible that subtle cultural anomalies may have been misinterpreted as geologic or hydrologic anomalies.

Appendix I: Geophysical Methods

Magnetic and electromagnetic conductivity data were acquired from both airborne and ground surveys. Fugro Airborne Surveys of Mississauga, Ontario, Canada conducted the airborne surveys Aug 9-17, 2000. The follow-up ground survey was conducted Oct 16-18, 2000 by National Energy Technology Laboratory (NETL) personnel.

Magnetic data were acquired to determine differences in the earth's magnetic field, which reflect differences in the local abundance of magnetic minerals. Magnetic data is especially useful for locating faults and geological contacts. Magnetic surveys are also sensitive to scrap metal that is commonly discarded on mine sites.

Electromagnetic (EM) conductivity techniques measure the apparent conductivity of the earth by applying a time varying magnetic field. The applied magnetic field induces the eddy currents within subsurface conductors, which in turn generate a secondary magnetic field that can be detected at the ground's surface or from low-flying aircraft. The strength of both the primary (applied) magnetic field (H_p) and secondary magnetic field (H_s) are measured using a single receiver antenna and are distinguished based on intensity, phase, or direction. The ratio (H_s/H_p) is linearly proportional to the ground conductivity.

$$H_s/H_p = i\omega\mu_0\sigma s^2/4$$

where: H_s = secondary magnetic field; H_p = primary magnetic field; $\omega = 2\pi f$; f = frequency (Hz); μ_0 = magnetic permeability of free space; σ = ground conductivity (siemens/m); s = intercoil spacing (m); and $i = \sqrt{-1}$.

A low induction number (conductivities < 100 mS/m) makes the general relationship between the ratio of the primary and secondary and electromagnetic conductivity methods possible. The induction number, B , is dependent on the intercoil spacing and the skin depth:

$$B = s/\delta$$

where: s = intercoil spacing; and δ = skin depth (McNeill 1980). The skin depth is described as the depth at which the amplitude of the electromagnetic field drops to $1/e$ of the source amplitude (e being the natural base). Skin depth is a function of the transmitter frequency (f) and ground resistivity (ρ). The exploration depth or skin depth (δ) for EM conductivity is determined by:

$$\delta = 504 \sqrt{\rho/f}$$

As implied by this relationship, increases in ground conductivity and frequency will decrease the skin depth, and therefore, decrease the depth of investigation (McNeill 1980).

Airborne surveys used transmitter-receiver coil pair antennae operating at different frequencies to obtain different exploration depths. From the above equation, one can see that the exploration depth increases with decreasing transmitter frequency. Furthermore, the exploration depth decreases with increasing ground conductivity (σ) because $\sigma = 1/\rho$.

For ground surveys, different exploration depths were obtained by changing the orientation of the transmitter and receiver coils and by varying the separation distance between the transmitter and receiver. The Geonics EM34-3XL that was used for ground electromagnetic surveys consisted of a transmitter and a receiver coil pair that was separated by either 20 or 40 m. Measurements were taken with the coil pairs in the horizontal dipole mode and the vertical dipole mode. These orientations can be best visualized by thinking of the coils as bicycle wheels, which they superficially resemble. In the horizontal dipole mode, the coils were oriented vertically, like a bicycle wheel. The magnetic dipole would be the imaginary axle for the wheel that is perpendicular to the coil, but parallel to the ground and therefore, horizontal. In the vertical dipole mode, the coils would be held parallel with the ground and the dipole would be vertical. The exploration depth (δ) can be approximated using the coil orientation and separation (s): for the horizontal dipole $\delta \cong 0.75 s$; for the vertical dipole $\delta \cong 1.5 s$. Therefore, the first approximation of exploration depth would be: 15 m for horizontal dipole, 20-m coil separation; 30 m for horizontal dipole, 40-m coil separation; 30 m for vertical dipole, 20-m coil separation, and 60 m for vertical dipole, 40-m coil separation.

The theoretical depth response of the EM34-3XL (McNeill 1980) using a vertical dipole coil orientation is shown in Figure 15. Transmitter-receiver separations of 20 and 40 m are shown as red and blue lines respectively. Also shown is the down-hole conductivity log for drill hole MW-3D (Figure 15),

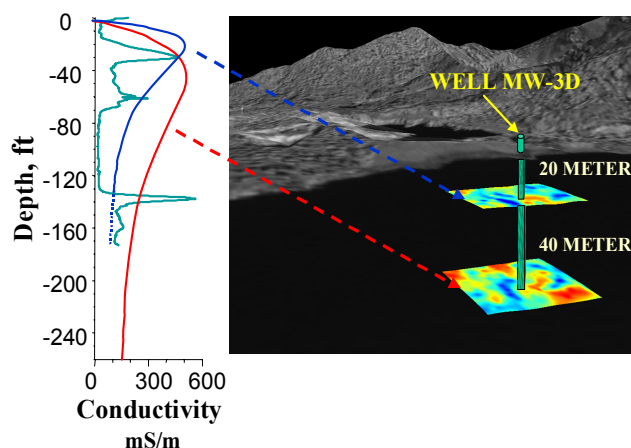


Figure 15. Response curves that relate vertical dipole EM34-3XL data to conductivity measurements in a borehole

which was provided by Tetra Tech EM. The conductivity log indicates 3 zones of anomalous conductivity: zone 1 from 15 to 36 ft; zone 2 from 55 to 65 ft; and zone 3 from 130 to 145 ft. The water table is located within zone 1, which is comprised of waste rock material excavated from Hermann Pit. Conductive zone 2 is within an interval of lake sediments where the anomalous conductivity may be due to a local aquifer or a layer of conductive clay. Conductive zone 3 is within the porous lower part of an andesite lava flow (Reller 2001).

The vertical dipole orientation is not sensitive to near-surface conductors; the maximum sensitivity is at a depth of about 0.4 times the intercoil separation (8 m at 20-m separation; 16 m at 40-m separation). Conductive zones 1 and 2 can be detected when the vertical dipole orientation is used with a 20-m transmitter-receiver separation. When a 40-m transmitter-receiver separation is used, all three conductive zones should be detected with the vertical dipole orientation.

The combined data from the 20-m horizontal dipole survey, the 20-m vertical dipole survey, and the 40-m vertical dipole survey are used to determine the depth of conductive zones. Near-surface conductive zones are depicted in the 20-m horizontal dipole survey. The 20-m vertical dipole survey is used to represent depths from 3-15 m (the vertical dipole orientation is not sensitive to the near surface). For the detection of conductive zones at greater depths, data from the 20-m vertical dipole survey can be subtracted from data from the 40-m vertical dipole survey. The difference can then be plotted to determine the lateral distribution of deep conductors.

Appendix II: Grid for Ground Geophysical Surveys

The grid for ground geophysical surveys was located on the waste rock dam between the Herman Impoundment and Clear Lake, an anomalous area identified by airborne conductivity surveys (Figures 6-11). This 200 by 220-m rectangular grid was oriented in a north-south direction with 20-m line spacing and 10-m spacing between stations. A Trimble XLR 4000 differentially-corrected global positioning system (DGPS) was used in conjunction with an OmniStar Inc. satellite broadcast differential correction service data to establish the location of each sampling point within the survey grid with sub-meter accuracy. The north and south end nodes for 11 grid lines were established. These lines had a nominal interline spacing of 20 m. The grid lines were sometimes offset slightly east or west to avoid cutting larger trees. As a result, some deviations in interline spacing occurred in the southern part of the grid.

A 10-m interval was established between stations along each line to simplify spacing requirements for the EM-34XL terrain conductivity instrument. This interval was established using a Brunton compass and fiberglass survey tape, and was not corrected for slope. Non-conducting plastic flags were used to mark station locations, which were sequentially numbered. Once the lines were cleared and stations established, an accurate location for each station was acquired using DGPS. The latitude, longitude and elevation were then converted to the appropriate datum and projection for the purpose of mapping geophysical data sets.

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References

- Fugro Airborne Surveys (2000) Helicopter-borne Dighem EM/magnetic geophysical survey of the Sulphur Bank Mine, Clearlake, CA. Final Report, Subcontract 00-C561-F for MSE Technology Applications, Butte, MT
- Hammack RW, Veloski GA, Sams JI Jr, Mabie JS (2002a) The use of airborne EM conductivity to locate contaminant flow paths at the Sulphur Bank Mercury Mine Superfund Site. Proc, Application of Geophysics to Engineering and Environmental Problems (SAGEEP, Feb 11-13, 2001), Las Vegas, NV
- Hammack, RW, Veloski GA, Sams JI Jr, Mabie JS (2002b) The use of airborne magnetic and EM conductivity surveys to locate groundwater flow paths at the Sulphur Bank Mercury Mine Superfund Site. Proc, National Mtg of the American Soc of Mining and Reclamation, Lexington KY
- Hearn, BC, Donnelly-Nolan J, Goff F (1995) Geologic map and structure sections of the Clear Lake Volcanics, northern California. USGS Misc Invest Series, Map I-2362, 1:24,000 scale, 3 sheets
- Isherwood WF (1975) Gravity and magnetic studies of The Geysers-Clear Lake Geothermal Region, California, USA. USGS Open File Report 75-368
- McNeill JD (1980) Electromagnetic terrain conductivity measurement at low induction numbers. Geonics Ltd Technical Note 6, 15 p
- Reller G (2001) Oral communication, Tetra Tech EM, Rancho Cordova, California
- Stimac JA, Goff F, Wohletz K (2001) Thermal modeling of the Clear Lake magmatic-hydrothermal system, California, USA. *Geothermics* 30: 349-390
- U.S. EPA (1994) Remedial Investigation/Feasibility Study: Sulphur Bank Mercury Mine Superfund Site, Clear Lake Oaks, California. U.S. Environmental Protection Agency, Region 9, San Francisco, CA
- White DE, Roberson CF (1962) Sulphur Bank, California, a major hot-spring quicksilver deposit. *Geol Soc Amer, Buddington Vol*, p 397-428